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OBSERVATIONS OF GALACTIC INFRARED SOURCES

MARTIN O. HARWIT, JAMES R. HOUCK,
JUDITH L. PIPHER, and BARUCH T. SOIFER

Center for Radiophysics and Space Research, Space Science Building
Cornell University, Ithaca, N. Y. 14850

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on

Flight 2

1 November 1971

Contract Monitor: Stephan D. Price
Optical Physics Laboratory

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A) Rocket Infrared 4-Color Photometry of the Galaxy's Central Regions,

B) Why Many Infrared Astronomical Sources Emit at 100 μm.

The first of these papers has been published in the Astrophysical Journal Letters (169, L31). The second paper has been submitted for publication to the journal Nature.

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ROCKET INFRARED 4-COLOR PHOTOMETRY OF THE GALAXY'S CENTRAL REGIONS

J.R. Houck,* B.T. Soifer, Judith L. Pipher+ and Martin Harwit**

ABSTRACT

The central portion of the Galaxy was observed in the bandwidths 5-6, 12-14, 16-23 and 85-115μ during an Aerobee 170 rocket flight launched on July 16, 1971. We report on measurements made during a 100 sec time interval around 21:56 MST. In addition to the galactic center, we also observed four new sources.

+ Now at the Dept. of Physics and Astronomy, University of Rochester

* Alfred P. Sloan Foundation Fellow

** Visiting astronomer at Kitt Peak National Observatory which is operated by the Association of Universities for Research in Astronomy Inc. under contract with the National Science Foundation.

On July 16, 1971 at 21:53 MST, an Aerobee 170 was launched from White Sands, N.M., The payload, consisting of a liquid helium cooled far infrared telescope, reached a maximum altitude of 190 km, and there were 280 seconds of useful observing time. We report here on 100 seconds of observations of the galactic center region, as measured by four infrared detectors with spectral bandwidths of 5-6, 12-14, 16-23, and 85-115μ. A more detailed report will be published later.

The telescope is similar to one flown previously (Harwit _et al._, 1969). It has an 18 cm diameter f/0.9 paraboloidal primary mirror. However, to avoid excess sensitivity to stray horizon radiation, secondary optics were added to improve the telescope beam pattern. These modifications will be reported elsewhere (Houck, 1971). They were considered necessary because the galactic center, as seen from a latitude 32°N, appears relatively low above the horizon. As in previous flights, the radiation was fully chopped by a tuning fork chopper, placed in the primary focal plane, and was then directed to the individual detectors through separate light pipes. This chopping procedure provided us with absolute flux levels for radiation coming from the individual $1/4^{\circ} \times 1^{\circ}$ rectangular fields viewed by the different detectors (see Fig. 1). In order to see small changes in flux levels over and above the scattered earth shine background, the data was displayed both in terms of absolute flux levels and in terms of instantaneous flux changes as determined by means of a differentiating amplifier. The raw data from the differentiating amplifiers is displayed in Fig. 2.

Five sources were detected near the galactic center (cf. Table I). Only the strongest of these, the galactic nucleus, has been previously reported. Fig. 1 shows the scan pattern of our four detectors relative to the galactic center as mapped by Hoffmann et al. (1970) at 100μ. The instantaneous fields of view of our detectors, at different times in flight, are known relative to one another with an accuracy of the order of 0.1°. [illegible] data comes from photographs of the sky taken with an aspect camera. There is, however, some uncertainty in the absolute pointing direction relative to the direction viewed by Hoffmann et al. We have therefore obtained a best fit relative to their isophote map, by comparing our actual scan pattern to synthetic scans across the map (see Fig. 1). We obtain a unique fit which gives excellent agreement both of the absolute brightness detected at 100μ and of the scan pattern as we cross the galactic center. Fig. 1 shows this signal on our first pass through the center.

Table I lists the total flux measured in each bandwidth for each of the sources observed. The procedure used to obtain these fluxes, involves subtraction of the scattered earth shine component using the method of Soifer et al. (1971) and Pipher et al. (1971). Errors in absolute calibration are very hard to assess, in an experiment of this kind. We assign a somewhat arbitrary uncertainty to our values, amounting to ± 50%.

The flux attributed to source III, the galactic center, was computed in a way somewhat different from that used by Hoffmann et al. We only integrated the total flux detected by our detector. However, on the assumption that the map produced by Hoffmann et al.

is correct -- and this appears to be true, at least for the portion through which we scanned -- we can extrapolate our data to obtain a flux value for the entire $3.6^{o} \times 2^{o}$ field covered by these authors. Our extrapolated value of 7×10^{-20} watt/m^2 Hz is in excellent agreement with their findings: a flux of 7.6×10^{-20} watt/m^2 Hz.

The agreement can be generally understood particularly because our galactic center measurements required very little background correction. In turn, this means that the differential chopping technique employed by Hoffmann et al. gives good flux levels, at least for this bright source. The general level of infrared emission from the galactic plane at 100μ does not appreciably contribute to the total flux reaching us from the central portions of the Galaxy.

Fig. 1 shows source II as a shoulder on source III -- the galactic center. This source was crossed by the 100μ detector on the scans made perpendicular to the galactic plane and actually appeared 20% brighter than seen in Fig. 2. It is this bigger flux which we list in the fifth column of Table I.

The fluxes measured for the galactic center by the short wavelength detectors are somewhat larger than those previously reported in the literature (Becklin et al., 1969 and Low et al., 1969). Because we are making absolute measurements, it is possible that a general background, not detected by the ground based observers added significantly to the measured flux.

We have no firm identifications for sources I and V, but a tentative assignment, respectively, to M8 and NGC 6357 seems reasonable on the basis of our aspect solution.

Acknowledgments

It is a pleasure to acknowledge the excellent support provided by Kitt Peak National Observatory's Rocket Branch Staff, directed by R. Nidey of KPNO, with the able assistance of T. Avery and V. Sinclair of KPNO. We also thank J. Labuda of Space General Corp., and R. Buck and staff of Oklahoma State University Research Foundation.

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TABLE I

Source	Total Flux (Watts/m^2-Hz)			
	5-6μ	12-14μ	16-23μ	85-115μ
I	$\leq 2.8\times10^{-24}$	1.8×10^{-23}	2.1×10^{-23}	6.2×10^{-21}
II	-	-	-	3.5×10^{-21}
III*	1.0×10^{-23}	5.1×10^{-23}	5.7×10^{-23}	5.7×10^{-20}
IV	$\leq 2.8\times10^{-24}$	1.6×10^{-23}	$\leq 1.5\times10^{-23}$	7.7×10^{-21}
V	4.4×10^{-24}	4.2×10^{-23}	6.5×10^{-23}	6.5×10^{-21}

*Galactic Center

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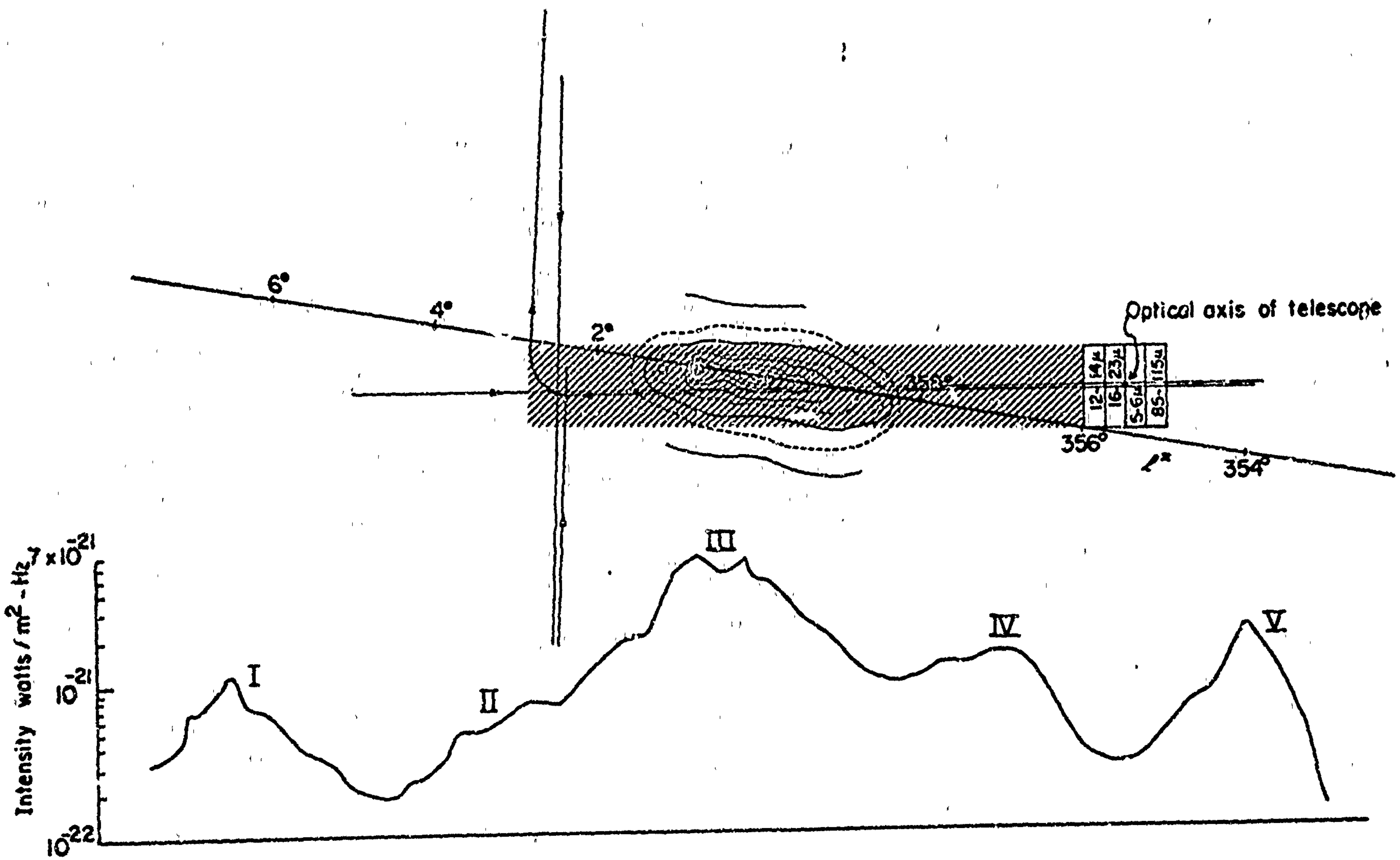
Figure Captions

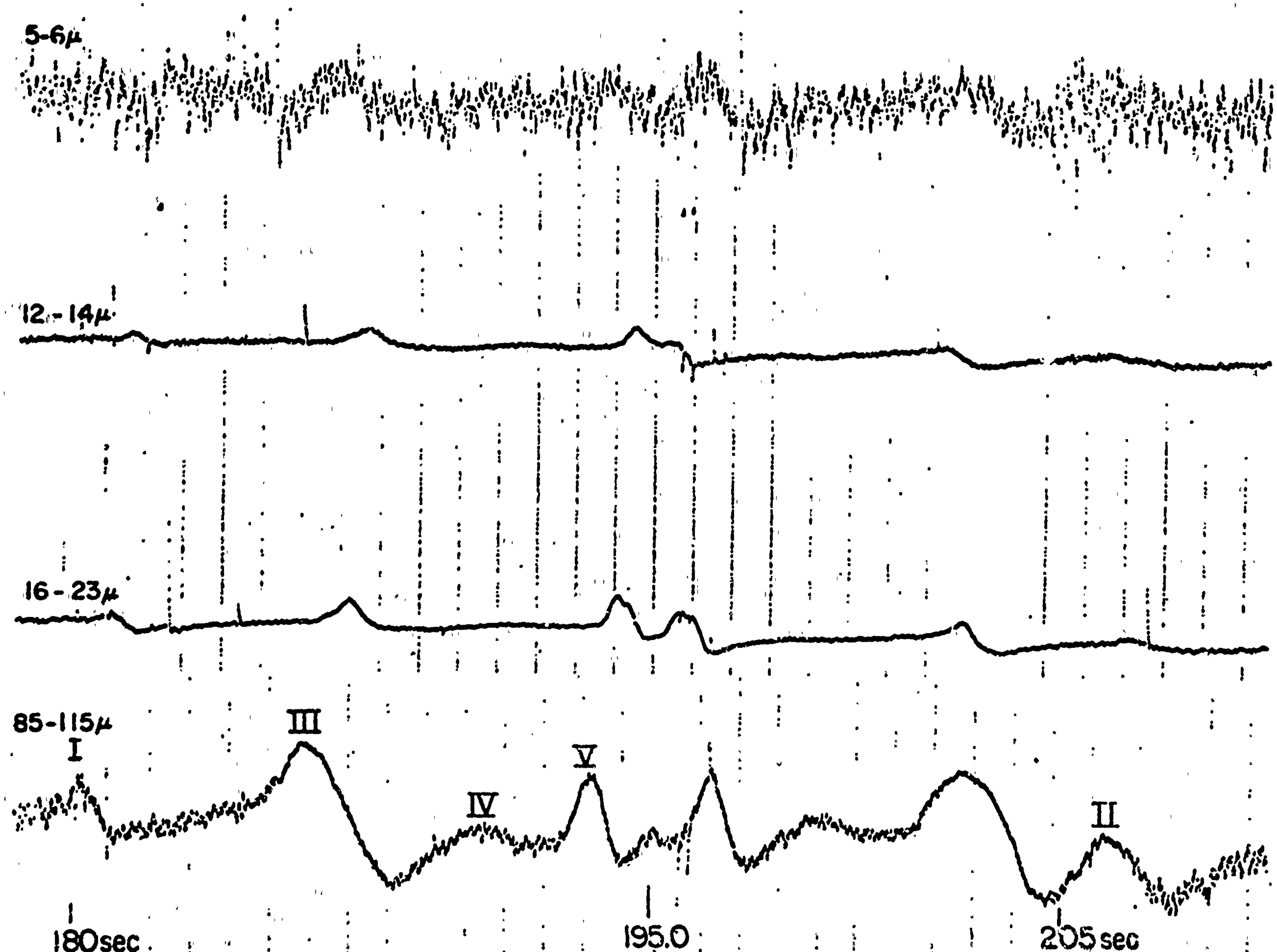
Fig. 1 Scan path of the detectors in Sagittarius region (cross hatched) superposed on Hoffmann's 100μ map of the Galactic center. The 100μ flux level as measured on the scan along the plane, in the direction of decreasing longitude is also shown. The fields of view of the four detectors, and their relation to the telescope optical axis are also indicated. The individual sources are labelled and referred to in the text. The galactic center is source III.

Fig. 2 The raw data for the four detectors. The data shown has been processed by a synchronous demodulator, a logarithmic amplifier, and a differentiating amplifier. This scheme enabled us to see point-like sources clearly, while rejecting slowly varying signals (such as the scattered earth shine). The sources are labelled as in Figure 1. Before 195 seconds, the detector passed over the sources in the sequence, 85-115μ, 5-6μ, 16-23μ and 12-14μ. After 195 seconds (reverse scan along the plane) this ordering is reversed. At 205 seconds, the scan perpendicular to the plane began, with no change in detector orientation.



Optical axis of telescope
6°
4°
2°
358°
356°
354°
12-14μ
16-23μ
5-6μ
85-115μ
l^{x}
Intensity watts / m² - Hz
7 x 10⁻²¹
10⁻²¹
10⁻²²
I
II
III
IV
V

8


5-6μ
12-14μ
16-23μ
85-115μ
I
III
IV
V
II
180sec
195.0
205 sec

WHY MANY INFRARED ASTRONOMICAL SOURCES EMIT AT 100μm

Martin Harwit[+], B.T. Soifer,
J.R. Houck* and Judith L. Pipher**

Recent far infrared observations indicate that three general features characterize many galactic sources:

1) the flux at 100μm is far greater than at the shorter, 20μ, 10μ and 5μ wavelengths[1] (Fig. 1)

2) at the shorter wavelengths sources appear more compact

3) there is a rough proportionality between the total infrared luminosity and the intensity of the thermal radio emission from these sources[2].

The third point strongly suggests that the far infrared sources all are associated with HII regions. But there are many puzzles. For example, it is surprising that the spectral characteristics of these sources appear so similar. Does this mean that spectral line or band emission is involved? If so, one might expect to learn about the chemical character of the emitting substances and decide about their structural properties -- atoms, molecules or grains. On the other hand, if

+Visiting astronomer at Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, etc., under contract with National Science Foundation.

*Alfred P. Sloan Foundation Fellow.

**Now at the Department of Physics and Astronomy, University of Rochester.

spectral emission features are not responsible for the high flux at 100μm, then thermal emission from grains at a color temperature of 30 to 60°K would provide the most likely explanation. In that case, however, it is puzzling that the observed color temperature could be so uniform for different sources.

The aim of this note is to show that line emission alone does not easily fit the facts but that a relatively narrow range of grain temperatures can be expected in the outer portions of many HII regions. These appear to be the prime infrared sources at 100μm.

Evidence that the observed emission does represent a continuum, rather than narrow band emission, is found in an intercomparison of our rocket observations[1] of the galactic center with balloon-borne studies by Hoffmann, Frederick and Emery[3]. The flux density -- energy emitted per unit spectral bandwidth -- at 100μm measured in these two experiments was practically identical, despite the fact that the spectral bandwidths differed by a factor of 2. This agreement favors continuum emission over discrete line emission. We will assume the continuum is due to thermal grain emission.

To explain the uniform heating of grains, we visualize a model of an HII region whose central portions may have more or less arbitrary electron density n_i, while a large enveloping region has an electron density n_e in the range $1 \leq n_e \leq 20\ cm^{-3}$. Such a density range probably is characteristic of the envelopes of most HII regions.

The model we present is similar to one developed by Krishna Swamy and O'Dell[4] to explain infrared emission in NGC 7027, by grain heating through resonantly trapped Lyman-α photons. The resonantly scattered Ly-α photons criss-cross the HII region in a random walk with steps short compared to the diameter of the region. Even when grain extinction for a single photon pass, straight through the HII region, is low, the resonantly scattered photons will be absorbed, since they traverse such a long path through the region. Each grain, effectively, has a larger absorption probability for trapped radiation.

The Ly-α flux is more or less uniform throughout the HII region because the random walk tends to smooth out the photon density. However where there are particularly strong sources of ionizing radiation an increase in grain temperature can be expected; and one also expects grains near the source of ionization, usually found in the central portions of a region, to be somewhat warmer simply because there will always be some direct absorption of ionizing radiation. These features are in general agreement with property 2) cited above.

Normally, however, the grain temperature at any given point in the HII region will be determined by the local Ly-α flux. For spherical grains, the temperature T depends on the Ly-α density $n_{Ly-\alpha}$ through the energy balance relation

$$4\epsilon_i \, \sigma T^4 \sim \alpha \, c n_{Ly-\alpha} \, \epsilon_u \qquad (1)$$

where σ is the Stefan-Boltzman constant, c is the speed of light; ϵ_i and ϵ_u are the infrared and ultraviolet emissivities of the grains and α is the Ly-α energy. The Ly-α photon density, in turn is determined by the formation rate and lifetime of these photons, and by the volume of the HII region. The formation rate of Ly-α photons integrated over the entire region equals the recombination rate

$$\dot{N}_{Ly-\alpha} \sim n_e n_p \; v \; \sigma_r \mathcal{V} \qquad (2)$$

where n_e, n_p are typical electron and proton number densities, v is the velocity of the particles, σ_r is the recombination cross section and $\mathcal{V}$ is the total volume of the ionized region.

The lifetime

$$\tau \sim \frac{1}{c \; n_g \; e_u \; \pi s^2} \qquad (3)$$

for spherical grains with number density n_g. Using (2) and (3) to determine $n_{Ly-\alpha}$, we obtain

$$n_{Ly-\alpha} \sim \frac{\dot{N}_{Ly-\alpha}\tau}{\mathcal{V}} \sim \frac{n_e n_p \; v \; \sigma_r}{c \; n_g \; \epsilon_u \; \pi s^2} \qquad (4)$$

The grain temperature can then be determined from (1) and (4) and is independent of ϵ_u.

$$T \sim \left[\alpha \frac{n_e n_p \; v \; \sigma_r}{n_g \; \epsilon_i \; \sigma \; 4\pi \; s^2} \right]^{1/4} \qquad (5)$$

One can see how this model fits the galactic center. Observations[1,3] show a total luminosity of $\sim 10^{42}$ erg sec^{-1},

indicating that two relations must hold. The Ly-α energy creation rate is

$$\alpha \dot{N}_{Ly-\alpha} \sim \alpha n_e n_p v \sigma_r \mathcal{V} \sim 10^{42} \text{ erg sec}^{-1} \qquad (6)$$

and the grain emission rate also is

$$n_g (4\pi s^2) \epsilon_i \sigma T^4 \mathcal{V} \sim 10^{42} \text{ erg sec}^{-1} \qquad (7)$$

These two expressions, of course, also give rise to (5). In equation (6), the observed volume[1,3] $\sim 3 \times 10^{62}$ cm^3, $\alpha \sim 1.6 \times 10^{-11}$ erg, $v \sigma_r \sim 5 \times 10^{-13}$ cm^3 sec^{-1} so that $n_e \sim n_p \sim 20$ cm^{-3}. With this number density and a line of sight depth equal to the observed 100μm width $\sim 10^{21}$ cm of the region, we obtain an emission measure of $\sim 12 \times 10^4$ cm^{-6} pc. Downes and Maxwell[5] have used the radio brightness temperatures to obtain an emission measure of 4×10^4 cm^{-6} pc for the extended source. This agreement is satisfactory particularly since our computed value is the effective emission measure for the entire region, while their's involves only the diffuse component which should be lower.

In equation (7) more of the parameters are uncertain. We let cosmic chemical abundance considerations dictate that

$$n_g \frac{4\pi}{3} s^3 \rho \sim \frac{n_p m_H}{300} \qquad (8)$$

where the grain density $\rho \sim 1$ g cm^{-3} and $m_H \sim 1.6 \times 10^{-24}$ g is the mass of hydrogen. Letting $s \sim 5 \times 10^{-6}$ cm then gives $n_g \sim 2 \times 10^{-10}$ cm^{-3} $\sim 10^{-11} n_p$ and

$$\epsilon_i T^4 \sim 5 \times 10^2 \ .$$

ϵ_i is very uncertain. To obtain a temperature of about 40^oK, consistent with the observed spectral shape, we choose $\epsilon_i \sim 1.5 \times 10^{-4}$ at 100μm. This emissivity would agree with a scaling law somewhere between λ^{-1} and λ^{-2}.

In any case Purcell[6] has shown that ϵ_i has a maximum value which cannot exceed $\sim 3 \times 10^{-3}$, at this temperature, even if the static dielectric constant were as high as 4. With the absorbance ratio (8) this leads to a lower limit for T at $\sim 20^oK$. We can see that our data limits the range of grain dimensions. Optical studies already had shown that interstellar grains are small compared to the wavelength of visible light. Their radii, $s < 2.5 \times 10^{-5}$ cm. They must, however, be larger than $s \sim 2.5 \times 10^{-7}$ cm; otherwise the small heat capacity of the grains would require either heating beyond 60^oK, even for single absorbed ultraviolet photons, or else would entail some form of fluorescence by the absorbing grains. Since, however, an overwhelming fraction of the observed energy is emitted (Fig. 1) near 100μm, with only a small amount of radiation observed at shorter wavelengths, appreciable amounts of fluorescence or grain temperatures higher than $\sim 60^oK$ cannot be allowed and grains smaller than $s \sim 2.5 \times 10^{-7}$ cm must be ruled out. This comes about because the emissivity at 100μm is so small, already, that unrealistically small emissivities, $\epsilon_i \leqslant 10^{-4}$, would be required at the shorter wavelengths, to limit emission. Our data would seem to preclude the possibility both of Platt[7] grains and of the very small grains postulated by Hoyle and Wickramasinghe[8].

For general galactic HII regions, grains should have substantially the same properties found near the Galaxy's center and we therefore postulate that s, ϵ_i, n_p/n_g are constant for the interstellar medium. The grain temperature (5) will therefore only vary as the fourth root of the electron density, and -- through the term $v\sigma_r$ -- on the fifth root of the plasma temperature. This gas temperature normally does not range more than a factor of 2 above or below 7000°K. The electron density in the outer envelope of HII regions may range from $n_e \sim 1$ cm^{-3} in normal regions of the disk, to $n_e \sim$ 20 cm^{-3} in the central portions of the Galaxy. The grain temperature in such regions should therefore generally not vary by more than 50% from some mean value. A range of 30° to 60°K, for example, would fit the observations reasonably well.

In discussing the galactic center, Krishna Swamy[9] has described a dust model different from ours. The grains are directly illuminated by stars rather than by repeatedly scattered Ly-α radiation. A difficulty he cites is the high dust opacity which then is needed. He finds that such an opacity is inconsistent with the observations at 2.2μm. Our model does not need these high opacities, since resonantly scattered radiation has a much higher probability for absorption by grains than does starlight which necessarily crosses an HII region in a single pass.

A second difficulty mentioned by Krishna Swamy concerns the replacement of grains ejected from the galactic center by

radiation pressure. A very high production rate is required in his model. In our scheme, on the other hand, two factors circumvent the difficulty. First, the total number of grains needed at any epoch is smaller in our model; replacement would therefore require smaller dust production rates, on that score alone. However, there is a second important factor which also works in the right direction. The outward directed momentum carried by ultraviolet starlight is deposited into the gas that is being ionized; it is not directly deposited on the absorbing grains. If recombination of ionized gases leads to faster Ly-α photon production at the center than at the periphery of a cloud, this radiation then will exert a further pressure on the outer regions, but much of this pressure again acts on the gas. In our model, it is primarily the gas that is expanding outward and pulling along dust; this leads to smaller grain ejection velocities than those found in Krishna Swamy's model.

One of the features mentioned by Krishna Swamy does however seem to be important. While our model tends to give temperatures quite insensitive to the total luminosity of an HII region, there does exist some sensitivity to variations in gas and dust density. Such variations would cause some variation in the wavelength distribution of emitted far infrared radiation. While such variations occur, it does seem possible that the sharp peaking in the 100μm range also is emphasized by broad, but specific, emission features and that grains probably will

also be found to have fairly uniform chemical properties. In this connection, it is interesting that Krishna Swamy finds dirty ice and particularly silicates to give better agreement with existing data than do graphite grains.

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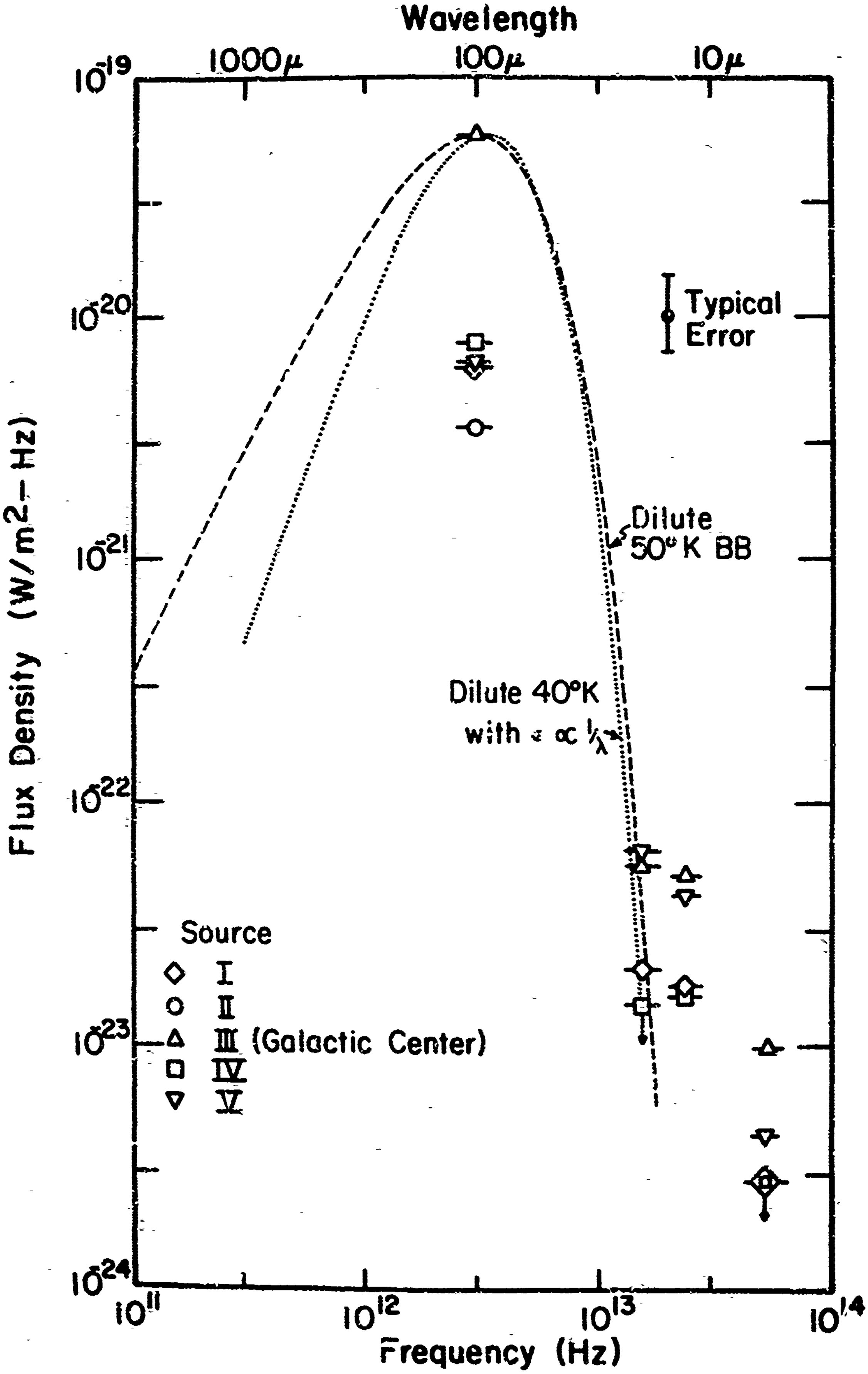
Figure Caption

Infrared fluxes for five sources measured by Cornell Group (Ref. 1). Source I and V have been tentatively identified with M8 and NGC 6357 respectively. The curves drawn represent different fits to the 100μm data for the galactic center. The black body emission BB can be ruled out on the basis of microwave data.[7]



Wavelength
1000μ
100μ
10μ
Flux Density (W/m²-Hz)
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
Typical Error
Dilute 50°K BB
Dilute 40°K with ε ∝ 1/λ
Source
I
II
III (Galactic Center)
IV
V
10¹¹
10¹²
10¹³
10¹⁴
Frequency (Hz)